Weather Effects on FSO Network Connectivity

Alexander Vavoulas, Harilaos G. Sandalidis, and Dimitris Varoutas

***Abstract*—The use of relays is one of the most promising methods for mitigating impairments of the performance of free-space optical (FSO) systems and extending their limited transmission range. However, several factors contribute to significant link performance degradation. Most severe is the influence of the adverse atmospheric conditions that frequently appear, thus making the design of strongly connected networks a demanding issue. In this paper, we consider a multiple-hop FSO network, where the nodes are distributed at fixed positions on a given path-link. We take account of the most critical weather phenomena, i.e., fog, rain, and snow, and derive analytical expressions for the node isolation probability, assuming a suitable path loss model. Next, we find the number of transceivers for a given path-link in order to achieve reliable performance. We also examine the reverse case; i.e., we find the total service length for a known number of FSO transceivers. The effect of the prime FSO modulation formats is also considered. The addressed analytical framework offers significant insights into the main factors that degrade the performance of FSO networks. It constitutes a valuable tool for telecom researchers to design such networks in practice.**

***Index Terms*—Free-space optics (FSO); Link budget; Multi-hop networks; Node isolation probability; Weather effects.**

I. Introduction

Free-space optics (FSO) is a cost-effective and high-bandwidth technique for transferring broadband services via point to point links. The way in which FSO transceivers operate is more or less the same as fiber optic ones; however, since laser signals are now transferred through the atmosphere, the path loss between the transmitter and the receiver becomes raised due to a plethora of pernicious factors that appear. Weather, propagation distance, scattering, absorption, turbulence, pointing error effects, laser wavelength, and data rates are some of the deterministic and random elements that contribute to the overall performance of an optical wireless link [1,2].

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Alexander Vavoulas is with the Department of Informatics and Telecommunications, University of Athens, Panepistimiopolis, GR-15784 Athens, Greece, and is also with the Department of Computer Science and Biomedical Informatics, University of Central Greece, Papasiopoulou 2-4, GR-35100 Lamia, Greece.

Harilaos G. Sandalidis (e-mail: sandalidis@ucg.gr) is with the Department of Computer Science and Biomedical Informatics, University of Central Greece, Papasiopoulou 2-4, GR-35100 Lamia, Greece.

Dimitris Varoutas is with the Department of Informatics and Telecommunications, University of Athens, Panepistimiopolis, GR-15784 Athens, Greece.

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Even if all the deteriorating factors play a significant role, designers and implementers should particularly take meteorological phenomena into consideration when they intend to deploy a robust FSO network in practice. Fog, snow, and rain cause the scattering of laser signals in the atmosphere. Scattering makes a portion of the light beam traveling from a source deflect away from the intended receiver. Another atmospheric effect under clear weather conditions is the turbulence induced by random changes in the atmospheric refractive index. As a result, random phase and irradiance fluctuations (scintillation) of the optical signals are observed at the receiver [3]. Furthermore, the FSO links also depend on the pointing error performance. Pointing errors occur due to mechanical misalignment or errors in tracking systems. Among all phenomena, fog brings about the greatest repercussions since it is constituted of small water droplets having dimensions near the size of infrared wavelengths. Snow and rain also influence the FSO performance, though their impact is significantly less than that of fog. Note that these weather phenomena rarely occur concurrently, and that helps in studying their effects separately [4,5].

An efficacious solution to mitigate the impairments on the performance of FSO systems is to employ relay-assisted techniques. In a multi-hop transmission, the total transmission path is divided into smaller distances between relays or hops which suffer from less loss. At each relay, the received optical field is processed and forwarded to the next one. In that way, an effective serial relayed network can provide services at far distances [6]. The proper operation of multi-hop networks requires, however, the satisfaction of connectivity among its nodes. A network is said to be fully connected when a path exists from any node to another. The absence of any path between at least one source–destination pair means that the network is said to be disconnected [7]. A critical metric to characterize connectivity is the isolation probability, defined as the probability that a random node cannot communicate with any other nodes [8].

Connectivity seems to have a critical role in wireless networks since the emergence of possible outages in their operation is more frequent than in wireline systems. As the exploitation of the RF band is the common way to provide telecom services on air, the majority of current connectivity studies deals with the performance of radio, mobile, and wireless sensor networks. Typical studies of this kind include [9] and [10]. In the context of optical wireless networking there appears to be an absence of similar works in the open technical literature mainly because the interest in this specific field is nowadays in season. That was the key motivation for our team to start working on this

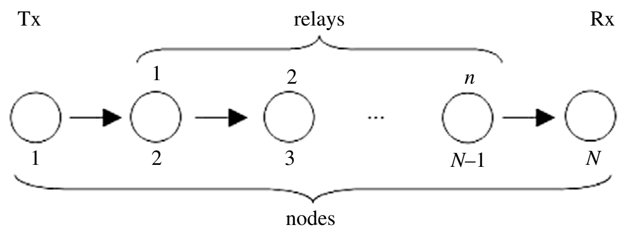

Fig. 1. Network architecture.

subject, publishing the first papers in the area of ultraviolet communications (see [11] and [12]). However, connectivity issues are much more challenging in the case of FSO networks which suffer mainly from adverse weather conditions. To the best of the authors' knowledge, there does not exist a detailed analysis, and the present study aims to fill this gap.

The rest of the paper is organized as follows. Section II presents, in brief, the assumptions followed by the FSO network model under examination. It summarizes the fundamental concepts of the node isolation probability assuming that the nodes are distributed according to a realistic point-process distribution. It also describes the basic link budget equation focusing on the attenuation effects induced by the main meteorological phenomena including fog/haze, rain, and snow as well. The minimum transmission range of transceiver nodes under the action of the dominant weather effect on the link is finally derived. In Subsection II.C, we evaluate the number of transceivers for a given path-link in order to achieve reliable performance. We also examine the reverse case, i.e., find the service length assuming a known number of FSO transceivers. In all cases, proper parameter values corresponding to practical systems are taken into account. The analysis is completed by investigating the trade-off of node isolation probability and probability of error for some basic modulation schemes used in FSO transmission. Finally, concluding remarks are given in Section IV.

II. Model Assumptions

A. Node Distribution Model

An appropriate spatial node distribution model is necessary in order to efficiently correspond to the dynamic topology of a communication network [13]. For wireless systems, the Poisson point-process (PPP) model is the most popular due to its simplicity [9]. The PPP model assumes a large number of transceivers randomly scattered over a limited service area, giving us the opportunity to consider a constant node density assumption. However, that approach is not accurate for networks in practice which often consist of a finite number of communication nodes. For that reason, the development of a more realistic model which assumes a known and fixed number of nodes independently distributed in a given region has been recently proposed in [14]. This model, known as the binomial point-process (BPP), can also find application for one-dimensional FSO networks where the nodes are placed several kilometers apart.

We therefore consider a serial network architecture composed of n relays, i.e., N FSO transceiver nodes uniformly distributed in a service interval of length ℓ according to a BPP model (see Fig. 1). The distance between a node and its k-th neighbor follows a generalized beta distribution given by [14]

$$f_{R_k}(r) = \frac{1}{\ell}\beta\left(\frac{r}{\ell};k,N-k+1\right), \tag{1}$$

where $\beta(x;a,b)$ denotes the beta density function defined as $\beta(x;a,b) = (1/B(a,b))x^{a-1}(1-x)^{b-1}$ and $B(a,b)$ the beta function defined by $B(x,y) = \int_0^1 t^{x-1}(1-t)^{y-1}\mathrm{d}t$.

A node becomes isolated when its first neighbor is beyond its communication range, R; thus, the node isolation probability, P_{iso}, can be readily derived as

$$\begin{aligned} P_{\text{iso}} &= \Pr(r \geqslant R) = 1 - \Pr(0 \leqslant r \leqslant R) \\ &= 1 - \int_0^R \frac{N}{\ell}\left(1-\frac{r}{\ell}\right)^{N-1} dr = \left(1-\frac{R}{\ell}\right)^N. \end{aligned} \tag{2}$$

From the above equation, we can conclude that an adequate node isolation probability for a given length, ℓ, depends on the minimum transmission range, R, and the number of nodes, N. That transmission range is directly related to the attenuation introduced by the appearance of fog, haze, rain, or snow that causes absorption and/or scattering of the transmitting optical signals. In view of the above, the present study derives the minimum number of nodes, N, which is necessary to attain network operation with node isolation probability close to zero.

B. Link Budget

In recent years, significant effort has been devoted to the development of a channel model to predict weather effects on FSO transmission [15]. A quite effective model for the link budget evaluation is described in [5] and also in [16]. According to this model, the received power is expressed as

$$P_r = P_t \frac{A_r}{(\Theta R)^2}\text{Att}, \tag{3}$$

where P_t is the transmitted power, Θ is the beam divergence, R is the link length, A_r is the receiver effective area, and Att is the atmospheric attenuation. The latter factor depends on the fog, haze, rain, or snow appearance.[1] In order to quantify the atmospheric attenuation, empirical models are usually adopted since theoretical approaches have an increased mathematical complexity.

More precisely, the attenuation of the optical signal at a distance R, due to fog and haze, is determined by the Beer–Lambert law [17]:

$$\text{Att}_{\text{fog}} = e^{-a_{\text{fog}}R}, \tag{4}$$

[1] It is mentioned that other system and channel dependent losses, e.g., receiver optical losses, loss due to beam wander, turbulence, etc., though important are not taken into account since we focus our study on the key attenuation introduced by the adverse atmospheric conditions.

TABLE I
RAIN CONDITIONS [19]

Precipitation	Amount (mm/h)
Light rain	2.5
Medium rain	12.5
Heavy rain	25
Cloudburst and heavy rain	100

where a_{fog} (in km^{-1}) is the attenuation coefficient, which is given by

$$a_{\text{fog}} = \frac{3.912}{V(\text{km})}\left(\frac{\lambda}{\lambda_0}\right)^q, \tag{5}$$

where V is the visibility, λ is the wavelength of the transmitted signal, λ_0 is the visibility wavelength reference, and q is the size distribution coefficient of scattering specified according to Kruse's model [18] by

$$q = \begin{cases} 1.6 & \text{if } V > 50 \text{ km}, \\ 1.3 & \text{if } 6 \text{ km} < V < 50 \text{ km}, \\ 0.585\ \text{V}^{1/3} & \text{if } V < 6 \text{ km}. \end{cases} \tag{6}$$

As a rule of thumb, fog appears when the visibility is less than 1 km. On the other hand, haze is present when the visibility ranges from 2 km to 5 km [19].

Raindrops of large enough size also cause reflection and refraction of optical signals. The specific attenuation[2] (in dB/km) is obtained as [20]

$$\text{Att}_{\text{rain}} = k_1 \mathcal{R}^{k_2}, \tag{7}$$

where $\mathcal{R}$ is the rain rate in mm/h (see Table I) and k_1, k_2 are model parameters which depend on both rain drop size and rain temperature. The values of these parameters have been recommended by ITU-R [20]. In the present work, we adopt the values $k_1 = 1.58$, $k_2 = 0.63$, which are based on measurements with $\mathcal{R}$ up to 90 mm/h.

Snow attenuation is classified into dry and wet [21]. Wet snow is partially melted and denser while dry snow is less dense and easily drifted by the wind. The specific attenuation (in dB/km) is given by [20]

$$\text{Att}_{\text{snow}} = b_1 \mathcal{S}^{b_2}, \tag{8}$$

where $\mathcal{S}$ is the snowfall rate in mm/h and b_1, b_2 are wavelength functions. Estimated values for dry snow are given as

$$\begin{aligned} b_{1,d} &= 5.42 \times 10^{-5}\lambda + 5.50, \\ b_{2,d} &= 1.38, \end{aligned} \tag{9}$$

whereas for wet snow as

$$\begin{aligned} b_{1,w} &= 1.02 \times 10^{-5}\lambda + 3.79, \\ b_{2,w} &= 0.72. \end{aligned} \tag{10}$$

[2] The term "specific attenuation" implies attenuation per unit length.

TABLE II
SYSTEM MODEL PARAMETERS [16]

Parameter	Value
Wavelength λ	780 nm
Visibility wavelength reference λ_0	550 nm
Tx power P_t	80 mW
Beam divergence Θ	5 mrad
Rx dimension	15 cm
Rx sensitivity	2 µW
White noise power spectral density N_0	10^{-14} W/Hz
Length of PPM symbol M	4
Network length ℓ	50 km

C. Minimum Transmission Range

The minimum achievable transmission range of each transceiver strongly depends on the prevailing weather conditions on the FSO links. It can be readily obtained by substituting Eq. (4), Eq. (7), or Eq. (8) into Eq. (3) and solving for R, as

$$R_{\text{fog}} = \frac{2W_0\left(\frac{a_{\text{fog}}}{2\Theta}\sqrt{\frac{P_t A_r}{P_r}}\right)}{a_{\text{fog}}}, \tag{11}$$

$$R_{\text{rain}} = \frac{2W_0\left(\frac{\ln z_1}{2\Theta}\sqrt{\frac{P_t A_r}{P_r}}\right)}{\ln z_1}, \tag{12}$$

$$R_{\text{snow}} = \frac{2W_0\left(\frac{\ln z_2}{2\Theta}\sqrt{\frac{P_t A_r}{P_r}}\right)}{\ln z_2}, \tag{13}$$

where $z_1 = 10^{k_1 \mathcal{R}^{k_2}}$ and $z_2 = 10^{b_1 \mathcal{S}^{b_2}}$. In the above equations, $W_0(\cdot)$ denotes the principal real-valued branch of the Lambert W function.[3] We can also derive analytical expressions for the node isolation probability by substituting the variable R of Eq. (2) by the values given by Eqs. (11)–(13).

III. NUMERICAL RESULTS AND DISCUSSION

This section presents some case studies for the design of robust FSO networks under various weather conditions. The first case investigates how many nodes are necessary to cover a service interval with given length and $P_{\text{iso}} \approx 0$. In contrast, the second scenario examines the range of an FSO network assuming a given number of transceivers. We use a typical set of model parameters, given in Table II, which is kept constant unless specified otherwise.

A. Number of Transceivers for a Given Service Length

Figure 2 visualizes the impact of fog and haze on the node isolation probability for typical values of V assuming ℓ = 50 km. At first, we observe that as V increases, the required

[3] The Lambert W function has two real branches: the branch $W_{-1}(x)$ for $x \in [-e^{-1}, 0]$ and the principal branch $W_0(x)$ for $x \in [-e^{-1}, \infty]$. It is noted that the Lambert function is implemented in several mathematical software products; e.g., see the function ProductLog in [22].

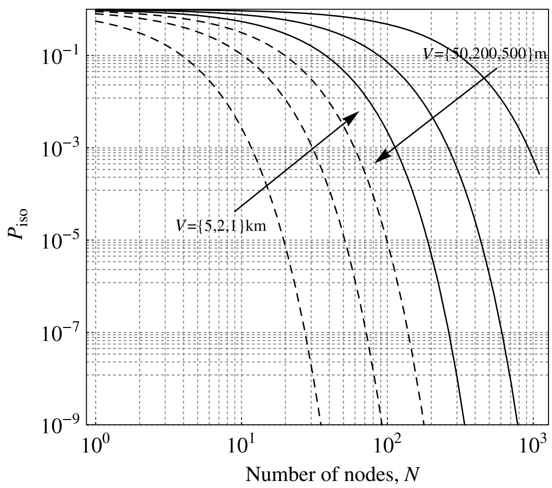

Fig. 2. Node isolation probability versus number of nodes for fog (continuous lines) and haze (dashed lines) conditions.

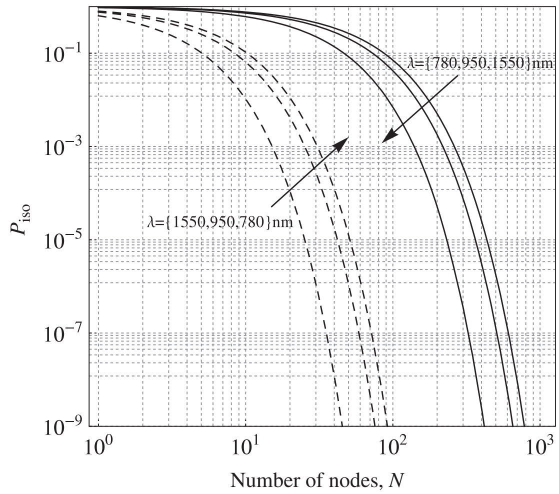

Fig. 3. Node isolation probability versus number of nodes and $\lambda = \{780, 950, 1550\}$ nm for fog (continuous lines and $V = 2$ km) and haze (dashed lines and $V = 200$ m) conditions.

number of nodes gets significantly reduced. This is expected, since larger values of V correspond to clearer atmospheric conditions. More precisely, an increase in the visibility by a factor equal to four (from dense fog with $V = 50$ m to thick fog with $V = 200$ m) decreases by 3.5 times the number of required nodes in order to achieve $P_{\text{iso}} = 10^{-3}$. For $V =$ 500 m this number is further reduced by a factor of 2. Haze, on the other hand, appears to have a better impact on the performance though it still reduces the number of required nodes; a visibility improvement from $V = 50$ m to $V = 5$ km decreases the number of required nodes by a factor of 80.

The choice of the operating wavelength is a critical issue. In practice, the common candidates are wavelengths of 780 nm, 950 nm, and 1550 nm, respectively [23,24]. This happens since the optical components that are commercially available are constructed to operate at these specific wavelengths following the specifications of the ones used in fiber optic communications. Generally speaking, the longer wavelengths are more resistant to fog attenuations [23].

Figure 3 demonstrates the impact of fog ($V = 200$ m) and haze ($V = 2$ km) on the node isolation probability for characteristic wavelengths, λ, assuming $\ell = 50$ km. Here, we observe that the number of required nodes to achieve $P_{\text{iso}} =$ 10^{-3} increases by a factor of 2 for $V = 200$ m and $V = 2$ km as the operating wavelength reduces from 1550 nm to 780 nm, confirming, thus, the assertion that operation at 1550 nm is considerably more robust.

The impact of rain attenuation is depicted in Fig. 4. The increase of rain intensity from light rain to medium rain significantly increases the number of required nodes by a factor of 3. When the rain conditions worsen, this factor further increases to 5. An extreme amount of precipitation (>90 mm/h) requires a high density node deployment, so it is critical to collect the rainfall rate data at different intervals of the year in order to achieve a trade-off between network availability and the number of required nodes to achieve low values of P_{iso}.

Finally, Fig. 5 illustrates the impact of snow for various values of snowfall rate assuming $\ell = 50$ km. Apparently, wet

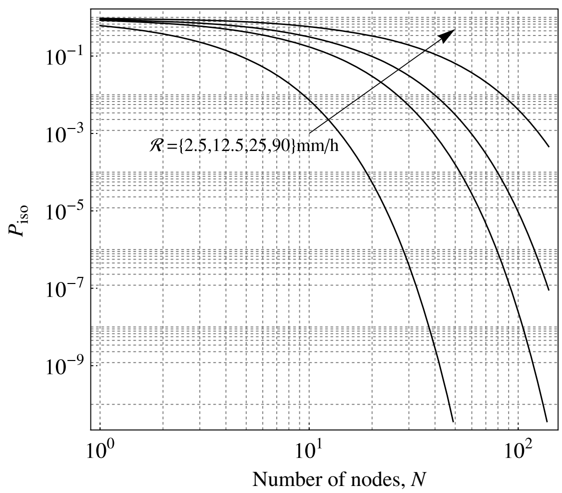

Fig. 4. Node isolation probability versus number of nodes and rain conditions.

snow conditions show an increased impact on the optical signal absorption compared with drier ones. This observation can also be extracted by comparing the two curves for a specific snowfall rate. More precisely, for $\mathcal{S} = 2$ mm/h two times the number of nodes are required under wet snow, whereas for $\mathcal{S} = 5$ mm/h this ratio is quadrupled.

B. Service Length for a Given Number of Transceivers

Table III presents results for the second scenario, where we consider a fixed number of transceivers, N, and look for the required network length, ℓ, in order to achieve P_{iso} close to zero. This scenario can inform network operators how to gradually deploy their networks in a geographical area taking into account the annual meteorological conditions. In the

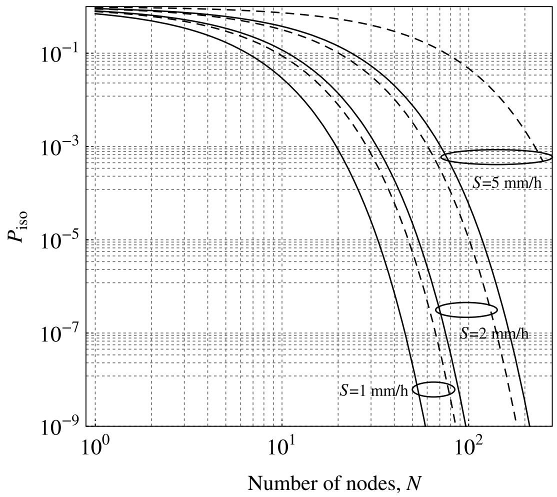

Fig. 5. Node isolation probability versus number of nodes for wet (dashed line) and dry (continuous line) snow.

case where thick fog is present for long periods of time, the deployment of an FSO network is unprofitable since only a few km are covered. On the other hand, haze and medium rain conditions are tolerable and a considerable service interval can be covered even with 10 transceivers. For example, with $V = 1$ km or with $\mathcal{R} = 25$ mm/h a service length of almost 11 km is covered. As was previously emphasized, wet snow is a dominant attenuation factor and medium to high snowfall rates lead to significant limitations. In more detail, a halved service length is given with a wet snowfall rate equal to 2 mm/h in comparison with a dry one. In contrast, low snowfall rates are sustainable for both wet and dry snow.

TABLE III
SERVICE LENGTH FOR $P_{\mathrm{iso}} = 10^{-3}$

	Fog		
V (km)	$N = 10$	$N = 20$	$N = 50$
0.05	0.74 km	1.27 km	2.88 km
0.2	2.61 km	4.46 km	10.11 km
0.5	5.94 km	10.14 km	22.96 km
	Haze		
V (km)	$N = 10$	$N = 20$	$N = 50$
1	10.98 km	18.76 km	42.46 km
2	20.20 km	34.50 km	78.07 km
5	44.72 km	76.37 km	172.85 km
	Rain		
$\mathcal{R}$ (mm/h)	$N = 10$	$N = 20$	$N = 50$
2.5	38.92 km	66.48 km	150.42 km
12.5	16.10 km	27.50 km	62.24 km
25	10.96 km	18.72 km	42.38 km
90	5.35 km	9.15 km	20.70 km
	Wet snow		
$\mathcal{S}$ (mm/h)	$N = 10$	$N = 20$	$N = 50$
1	21.58 km	36.85 km	83.41 km
2	9.31 km	15.91 km	36.00 km
5	3.02 km	5.15 km	11.66 km
	Dry snow		
$\mathcal{S}$ (mm/h)	$N = 10$	$N = 20$	$N = 50$
1	29.84 km	50.96 km	115.35 km
2	19.33 km	33.01 km	74.72 km
5	10.83 km	18.49 km	41.86 km

C. Modulation Impact

In this section, we investigate the impact of some common modulation formats in order to construct reliable FSO connections. The most fundamental modulation schemes used in optical wireless systems are on–off keying (OOK) and pulse position modulation (PPM) [25]. For the OOK scheme, the relationship between the minimum required received power, P_r, and the achieved probability of error, P_e, is given by [26]

$$P_r = \sqrt{N_0 R_b} Q^{-1}(P_e), \tag{14}$$

where R_b is the data rate, $Q(\cdot)$ is the Gaussian Q function defined as $Q(x) = 1/\sqrt{2\pi}\int_x^\infty \exp^{-\frac{t^2}{2}} dt$, and N_0 is the white noise power spectral density. The corresponding relationship for the PPM scheme is given by [26]

$$P_r = \sqrt{\frac{2N_0 R_b}{M\log_2 M}} Q^{-1}(P_e), \tag{15}$$

where M is the length of the PPM symbol. The minimum achievable transmission range in this case is obtained by substituting any of Eq. (4), Eq. (7), or Eq. (8) into Eq. (3), putting the obtained results into Eq. (14) or Eq. (15), and finally solving for R. After that process, the following expressions occur:

$$R_{\mathrm{fog,OOK}} = \frac{2W_0\left(\frac{a_{\mathrm{fog}}}{2\Theta}\sqrt{\frac{P_t A_r}{Q^{-1}(P_e)\sqrt{N_0 R_b}}}\right)}{a_{\mathrm{fog}}}, \tag{16}$$

$$R_{\mathrm{fog,PPM}} = \frac{2W_0\left(\frac{a_{\mathrm{fog}}}{2\Theta}\sqrt{\frac{P_t A_r M\log_2 M}{Q^{-1}(P_e)\sqrt{2N_0 R_b}}}\right)}{a_{\mathrm{fog}}}, \tag{17}$$

$$R_{\mathrm{rain,OOK}} = \frac{2W_0\left(\frac{\ln z_1}{2\Theta}\sqrt{\frac{P_t A_r}{Q^{-1}(P_e)\sqrt{N_0 R_b}}}\right)}{\ln z_1}, \tag{18}$$

$$R_{\mathrm{rain,PPM}} = \frac{2W_0\left(\frac{\ln z_1}{2\Theta}\sqrt{\frac{P_t A_r M\log_2 M}{Q^{-1}(P_e)\sqrt{2N_0 R_b}}}\right)}{\ln z_1}, \tag{19}$$

$$R_{\mathrm{snow,OOK}} = \frac{2W_0\left(\frac{\ln z_2}{2\Theta}\sqrt{\frac{P_t A_r}{Q^{-1}(P_e)\sqrt{N_0 R_b}}}\right)}{\ln z_2}, \tag{20}$$

$$R_{\mathrm{snow,PPM}} = \frac{2W_0\left(\frac{\ln z_2}{2\Theta}\sqrt{\frac{P_t A_r M\log_2 M}{Q^{-1}(P_e)\sqrt{2N_0 R_b}}}\right)}{\ln z_2}. \tag{21}$$

Then, we can derive analytical expressions for the node isolation probability by substituting the variable R of Eq. (2) by the values given by the Eqs. (16)–(21).

Table IV displays the required number of nodes in order to cover a network length of $\ell = 50$ km assuming the previously mentioned modulation schemes and $P_e = 10^{-6}$. In general,

TABLE IV
NUMBER OF REQUIRED NODES AND SUPPORTED DATA RATE FOR $P_{\mathrm{iso}} = 10^{-3}$ AND $P_e = 10^{-6}$

		OOK			PPM		
Weather condition	Parameter value	1 Mbps	100 Mbps	1 Gbps	1 Mbps	100 Mbps	1 Gbps
Fog	$V = 200$ m	407	478	523	389	454	495
Haze	$V = 1$ km	100	122	137	94	115	128
Light rain	$\mathcal{R} = 2.5$ mm/h	24	32	38	22	29	34
Medium rain	$\mathcal{R} = 12.5$ mm/h	60	75	86	57	70	79
Wet snow	$\mathcal{S} = 2$ mm/h	103	126	141	97	118	132
Dry snow	$\mathcal{S} = 2$ mm/h	50	63	72	47	58	66

the use of PPM is more profitable as the supported data rate increases for a given weather condition. More precisely, a data rate increase from 1 Mbps to 1 Gbps for PPM reduces the number of nodes by 1%–3% compared to OOK. Furthermore, as data rates increase and the weather conditions worsen, e.g., lower visibility or higher rainfall intensity, the increment percentage of the required nodes decreases. This is quite important since the demand for higher data rates is becoming more and more imperative.

IV. CONCLUSIONS

In this study, we focused on the node isolation probability of a serial FSO network where transceivers are placed on a given path-link following a one-dimensional BPP. We used an effective path loss model and considered operation under the most critical weather phenomena, e.g., fog, haze, rain, and snow. Proper design scenarios were presented in order to reveal the interaction between the number of required nodes, the length of the service interval, and the weather condition parameters (visibility, rainfall/snowfall rate) so as to achieve $P_{\mathrm{iso}} \approx 0$ as well. In the worst case scenario, i.e., thick fog with 50 m visibility, a network operator needs 15 nodes to cover a service length of 1 km (Table III). The work can be improved in a number of ways, e.g., by using different path loss models, considering other modulation formats, using forward error correction schemes, etc. These are necessary extensions since optical wireless communication is gaining particularly increased interest nowadays.

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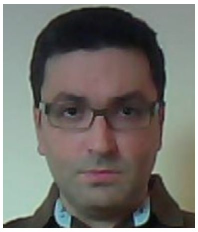

Alexander Vavoulas was born in Athens, Greece, in July 1976. He received his B.Sc. degree in Physics and M.Sc. degree in Electronics and Radio-Communications in 2000 and 2002, respectively, both from the University of Athens, Greece. He is currently working toward a Ph.D. degree at the same University.

Since 2009, he has been a member of the Special and Laboratorial Teaching Staff at the Department of Computer Science and Biomedical Informatics of the University of Central Greece.

His major research interests include physical and MAC layer issues for fixed broadband wireless access systems, optical wireless communications and technoeconomic evaluation of network services. He serves as a reviewer for several journals and conferences.

Harilaos G. Sandalidis was born in Florina, Greece, in 1972. He received a five year Diploma degree in Electronics and Computer Engineering and an M.Sc. degree in Business Administration from the Production Engineering and Management Department of the Technical University of Crete, Greece, in 1995 and 1998, respectively. He also received an M.Sc. degree in Radiofrequency and Microwave Communications and a Ph.D. degree in the Telecommunications area from the Electronics and Telecommunications (former Electronics and Electrical engineering) Department of the University of Bradford, UK, in 1996 and 2002, respectively.

During the period between 1996 and 2001, he was a research assistant at the Telecommunications Systems Institute of Crete, Greece, working toward his Ph.D. degree in collaboration with Bradford University. After his military service, he joined TEMAGON, the technology consulting branch of the Hellenic Telecommunications Organization (OTE Group), in 2002, where he was involved in the risk mitigation program for the 2004 Olympic Telecommunication Network in collaboration with Telcordia Technologies, Inc. He also worked as a senior investigator at the Greek Ombudsman Office. In March 2009, he joined the University of Central Greece, where he is a Lecturer in the Department of Computer Science and Biomedical Informatics.

His major research interests include optical wireless communications, computational intelligence, and heuristic optimization techniques with regard to their application to the telecommunications field.

Dimitris Varoutas holds a Physics degree and M.Sc. and Ph.D. diplomas in Communications and Technoeconomics from the University of Athens. He serves as an Assistant Professor in the Department of Informatics and Telecommunications at the University of Athens. He has participated in numerous European R&D projects in the RACE I&II, ACTS, Telematics, RISI, and IST frameworks in the areas of telecommunications and technoeconomics. He actively participates in several technoeconomic activities for telecommunications, networks, and services such as the ICT-OMEGA and CELTIC/CINEMA projects, as well as the Conferences on Telecommunications TechnoEconomics. He also participates in or manages related national activities for technoeconomic evaluation of broadband strategies, telecommunications demand forecasting, price modeling, etc. His research interests span the design of optical and wireless communications systems to technoeconomic evaluation of network architectures and services. He has published more than 80 publications in refereed journals and conferences in the area of telecommunications, optoelectronics, and technoeconomics, including leading IEEE journals and conferences. He is a member of the LEOS, Communications, Circuits and Systems, Education and Engineering Management Societies of IEEE and serves as a reviewer for several, including IEEE, journals and conferences. Since 2007, he has been the Deputy Vice Chairman of ADAE, the National Authority for Communications Security and Privacy.